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Economic and environmental impact assessment through system dynamics of technology-enhanced maintenance services

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Abstract

This work presents an economic and environmental impact assessment of maintenance services in order to evaluate how they contribute to sustainable value creation through field service delivery supported by advanced technologies. To this end, systems dynamics is used to assist the prediction of economic and environmental impacts of maintenance services supported by the use of an e-maintenance platform implementing prognosis and health management. A special concern is given to the energy use and related carbon footprint as environmental impacts.

Key words: system dynamics, equipment/energy efficiency, maintenance policies, maintenance services.

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1 Introduction

Due to the fierce competitive pressure companies in the Business to Business market are facing, it is more difficult to differentiate products only on the basis of technological superiority, margins associated to product sales are decreasing and there is a need to exploit new growth potential in mature markets. Then, services have become a source of competitive advantage (Cohen et al., 2006; Gebauer, 2008) and an increasing number of product-oriented companies is investing on the service business linked to their products (Gebauer and Puetz, 2009). This trend, known as servitization, refers to the process of creating value by adding services to products (Baines et al., 2009). In manufacturing industry, equipment builders following servitization are moving into a transition path towards becoming service providers. A first step implies the consolidation of product-related services (Oliva and Kallenberg, 2003); according to Sheng et al. (2009), *“the key to improve service for a manufacturer is to improve maintenance service”*.

Tsang (2002) suggests that the deployment of new technologies for maintenance is crucial to deliver better or innovative services to customers. In this regard, remote monitoring technology and Prognosis and Health Management (PHM) are envisaged to have an important role to support servitization in manufacturing (Grubic, 2014). Within the research priorities proposed by Ostrom et al. (2010), leveraging technology to advance service is seen as the pervasive force affecting all other research priorities categorized in three aspects, i.e. strategy, development and execution of services.

Further on, the role of maintenance from the perspective of equipment life cycle is to contribute to sustainable manufacturing by using predictive measures and implementing new technologies to this end (Garetti and Taisch, 2012). Overall, maintenance is seen as a means to enhance eco-efficiency during the equipment life cycle, while keeping availability, reliability, safety and maintainability beyond the conventional boundaries (Levrat et al., 2008).

Accordingly, with the envisaged trends, the research questions driving the present work are the following ones:

- Which value can a company achieve from this kind of technologies in terms of economic and environmental performances?
- Is there any relevant environmental impact reduction subsequent to the use of advanced technologies to support field service delivery to an installed equipment?

Such questions relate to understanding of levers for the competitiveness of Original Equipment Manufacturers (OEMs) implementing servitization. This paper refers then to the pervasive research priority identified by Ostrom et al. (2010), studying the adoption of technologies for PHM to enhance maintenance services in view of economic and environmental performances. System dynamics, selected due to its flexibility to model and simulate complex systems with many interlocked variables, is used to unveil the trade-offs between the two types of performance.

The work results from the demonstration phase of an EU funded project on “Sustainable value creation in manufacturing networks” (SustainValue) in collaboration with FIDIA, a machine tool builder. Section 2 of the paper consists in literature analysis presenting three reviews related to the research questions and focused on: the potentials of ICTs for the deployment of PHM, the performance measures to assess economic and environmental impacts, system dynamics and its support to decision-making in areas related to the scope of the work (operations, sustainability). Section 3 presents the modelling methodology proposed to assess the impacts when planning an offer for a maintenance service contract. Section 4 focuses on the use of the methodology for field service delivery planning to a single equipment at a customer site. Section 5 envisions the extension of the methodology to field service network planning.

2 Literature analysis

2.1. ICT potentials for Prognosis and Health Management

The integration between recent advances in ICT and Condition Based Maintenance (CBM) is traditionally discussed under the E-maintenance umbrella. E-Maintenance term was introduced at the beginning of 2000. Muller et al. (2007) finally gave birth to an E-maintenance definition, keeping in mind also the European standard (EN 13306: 2001): “*maintenance support which includes the resources, services and management necessary to enable proactive decision process execution. This support includes e-technologies (ICT, web-based, tether-free, wireless, infotronics technologies) but, also, e-maintenance activities (operations or process)*”. E-maintenance technologies are becoming relevant enablers for many issues in maintenance management. Typical examples of applications, discussed also in industry besides scientific context, are the following: to support the diagnosis of faults, to analyse the potential faults, to anticipate incoming failures, to plan maintenance interventions and related requirements for spare parts and technical personnel, to retrieve information for the improvement of product performance. Thus, through E-maintenance, CBM programs can bring benefits both for the customer, owner of the product/equipment, and for the OEM, provider of the maintenance services. Some references can be cited for further in-depth (Lee et al., 2006, Lee et al., 2011, Levrat et al., 2008, Muller et al., 2007).

Based on the information obtained by condition monitoring, CBM programs encompass two important aspects: diagnosis, concerning fault detection, isolation and identification when it occurs, and prognosis, considering fault prediction before it occurs (Jardine et al., 2006). Lee et al. (2006) define intelligent prognostics as “*a systematic approach that can continuously track health degradation and extrapolating temporal behaviour of health indicators to predict risks of unacceptable behaviour over time as well as pinpointing exactly which components of a machine are likely to fail*”. In general, it can be said that PHM integrates the interpretation of environmental, operational, and performance-related parameters for assessing the equipment health and predicting its remaining useful life (Guillen et al., 2013). Concretely, the estimation of the remaining useful life (RUL) could be applied to the whole system, part of a system or separated components and for each detected (current) or potential degradation / failure mode (Voisin et al., 2010).

2.2 Performance measures for economic and environmental assessment

Economic performance to evaluate alternatives have always been subject to a great interest in literature and in practice, due to its fundamental importance for organizations. The traditional economic performance measures are the well-known total costs and revenue estimations (for example, the Net Present Cost). Alongside to these are the project performance evaluation measures (an example is the Payback Period). Some authors maintain also that not only costs and revenues must be the focus of the economic evaluation, but also the revenue loss must be kept monitored (Chang and Lewins, 1996). This is relevant for maintenance: indeed, the theory of hidden costs considers costs resulting from performance losses, subsequent to downtimes/unavailability, non-quality/low product rate, etc... (Crespo et al., 2009, Salonen and Deleryd, 2011). The theory recommends the calculation of indicators separating the hidden from the visible costs (these include the resources directly spent in the maintenance budget, such as for spare parts or services from third parties, or indirectly, e.g. for maintenance coordinators or other roles in the staff).

The environmental dimension also received an extended exposition in literature: many authors have proposed formulas for the computation of many indicators. Energy consumption and global warming potentials are amongst the most relevant impact categories for companies, due to their strict regulations from governments and the increasing pressure from public opinion. Typical indicators for these impacts are, respectively, the needed kWh and the emitted kg of CO₂ equivalents. Although these are connected, i.e. the production and use of energy often lead to greenhouse gases emissions, they are not straight proportional. This happens because different CO₂ emissions are generated by different types of energy sources. For example, transportation may use different fuels, which are characterized by different emissions during extraction and use; electricity can be generated with alternative fuels, with renewable sources or with nuclear energy, and each country has its own source mix: all these are related to specific CO₂ equivalents emissions per produced unit of energy (Elsayed et al., 2003; Lenzen, 2008).

The meaning of CO₂ equivalents measure lies in the fact that the several greenhouse gases, which are main cause of the global warming, impact on the temperature raise potential to a different extent; a reference substance (carbon dioxide – CO₂) is defined, to which the other compounds are referred to through a multiplication factor which expresses the CO₂ equivalence for each of them (Narita et al., 2006). Thus, the total global warming potential of an industrial activity would be the sum, for all harmful substances, of the emitted quantity due to the system in question multiplied by the CO₂ equivalence factor of each substance.

Besides energy and global warming potential, literature presents other impact categories, as total resource depletion, expressed in kg (Ritthoff et al., 2002). Moreover, emissions lead to other impacts: authors suggest to consider indicators such as acidification, eutrophication, ozone depletion, resource consumption, waste generation, which are out of scope of this paper (Derwent et al., 1998; Pehnt, 2006; Seppälä et al., 2004; World Meteorological Organization, 2006).

2.3 System dynamics and its potentials in operations and sustainability

Sterman (2000) defines System Dynamics (SD) as “*a method for developing models and simulations (often computer simulation models) to help us learn about dynamic complexity*”. Thus, SD allows understanding changes of variables over time under the influence of causal relationships, dynamic complexity, and structural delays (Caulfield and Maj, 2002). In particular, the dynamic evolution of complex systems with interlocked variables – linked through feedback loops and time delayed relationships – can be generated by a SD model, exploiting also stochastic laws for some variables of interest, thanks to the use of Monte Carlo method.

Two advantages of using SD are, according to Azar (2012), an easy understanding of cause-effect interrelationships among different elements within a system, and the support to the identification of potential improvements of the system behaviour. SD is then applied in many fields, as environmental or public policy, corporate strategy, security, healthcare, business process development, biological and medical modelling, energy and environment, theory development in the natural and social sciences, dynamic decision making, study of complex nonlinear dynamics, software engineering, and supply chain management (Richardson and Otto, 2008; Suryani et al. 2010). This clearly demonstrates its flexibility. Considering the focus of this paper, recent works are reviewed as examples to prove the SD's potential to support decisions in operations management, and its relevance for the analysis of sustainability aspects.

Regarding decisions in operations, Suryani et al. (2010) build a SD model for forecasting demand and evaluating policy scenarios related to planned production capacity. Other applications have been made in health care for modelling patient length of stay (Walker and Haslett, 2001), in studies regarding resilience and improvement strategies of water management systems (Winz et al. 2009), in effects assessment of a biological release for building design, operation and retrofit (Thompson and Bank, 2010). A good number of concrete applications is also presented regarding supply chain management: Spengler et al. (2003) applied SD to spare parts management and component recovery in closed-loop supply chains; Ozbayrak et al. (2007) modelled a complex supply chain network and shed light on the interactions of its key system parameters; Georgiadis et al. (2005) applied SD for mapping and analyzing multi-echelon food supply chains. SD is also applied to maintenance services, to assess the introduction of preventive maintenance contracts on the overall service performance of a manufacturer of farm machinery (Legnani et al., 2010) and to support OEM – customer relationships when a maintenance service contract is set-up (Ferri et al., 2012).

SD is also applied to analyse sustainability aspects, with the purpose to identify the potential influence between environmental, social, economic impacts. For example, Guo et al. (2001) analyse the effects of industrial activities and wastewater treatment processes in the Xier River and the contributions of various nonpoint pollution sources to the lake's eutrophication problems, considering different alternatives to the system's environmental and socio-economic objectives. Dyson and Chang (2005) are using SD to predict the solid waste generation in a fast-growing urban area; Egilmez and Tatari (2012) studied the increasing CO₂ emission trend in the US highway system, by testing three strategies for policy making, i.e. fuel efficiency, public transportation and electric vehicle usage.

3 Modelling methodology

3.1 Overview

The methodology proposed for impact assessment is inspired by general principles of Systems Engineering (INCOSE, 2007). It can be considered in the frame of Reliability, Maintainability, Availability and Safety Engineering, a key process in Systems Engineering. Further on, it relates to the ability to sustain the operation of a system through logistics support (Pyster and Olwell, 2013). The methodology aims then at modelling the interaction between the product/equipment installed at a customer site, as primary system, and its maintenance logistics support, as enabling system during the equipment use life. The model would support the assessment of the economic and environmental performances of interest.

Considering the focus of this work, the enabling system is the *field service delivery process enhanced by the technological support of an e-maintenance platform*: the target reliability is considered as an

inherent characteristic of the equipment, while the maintenance logistics support is studied by assuming, amongst different scenarios, the use of an e-maintenance platform implementing PHM (Figure 1). In accordance to the relevance of energy consumption and global warming potentials, the environmental impact assessment concentrates on the energy consumed (kWh) and correspondent carbon footprint (CO₂ equivalents) along the equipment use life.

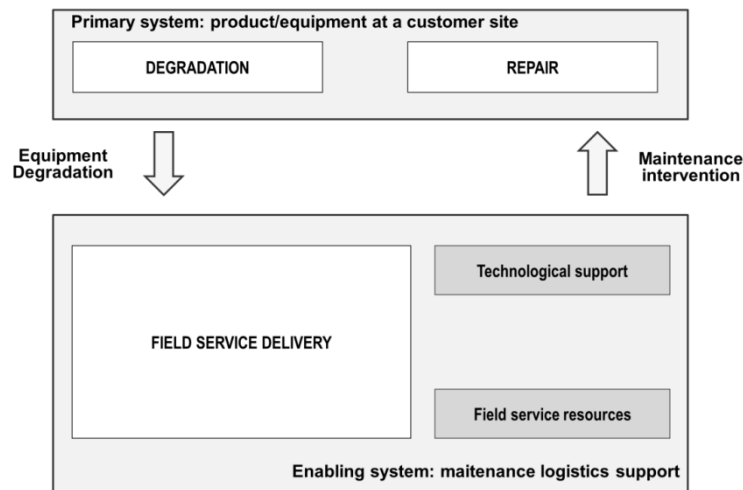


Figure 1 Systems of interests

The methodological approach proposed for this study (Table 1) starts with the first two steps providing requirements and data for building the SD model at a third step. The fourth and last step uses the SD model to predict and analyse the economic and environmental performances of alternative solutions of field service delivery offered in a contract.

#	Step	Objectives
1	State based modeling	- To model the degradation and repair processes of the target product/equipment
2	Component object and data modeling	- To model the maintenance logistics support, identifying resources and services required in relationship with the degradation and repair processes of the target product/equipment - To model reliability, maintainability and supportability data
3	Systems dynamics modeling	- To build the simulation model, based on building blocks designed according to the models built at previous steps
4	Economic and environmental impact assessment	- To integrate previous models with the performances target of assessment - To assess the economic and environmental performances of interest

Table 1 Modelling methodology

3.2 State based modelling

State based modelling is adopted to represent the degradation and repair processes of the product/equipment. Among several formalisms available – such as State Transition Diagrams (STDs), Markov Chains, Petri Nets or any of their extensions (Trivedi and Malohtra, 1993) – this work uses STD, exploiting its modelling features to represent, in a generic formalism, the transitions between discrete states together with their triggering events, actions carried on, and guarded conditions under which the transitions may happen. According to the formalism, a label along a transition is then reported as “event / action [condition]”. Figures 2 and 3 show the three STDs correspondent to the use cases considered for the target equipment. STD1 and STD2 (Figure 2) represent the case when a service contract supports only corrective maintenance, respectively:

- i) after the equipment presents a fault; thus, the maintenance intervention occurs after the customer issues a request due to a malfunctioning or fault state, corresponding to a complete stoppage of the equipment;
- ii) after the equipment presents a fault with the complete stoppage, or the customer detects a degradation of technical performance of the equipment leading to quality losses (i.e. higher product quality defects detected, for ex., by a control chart); thus, the maintenance intervention occurs after the customer issues a request due to a malfunctioning or fault state, corresponding to the equipment stoppage or the product quality defects.

STD3 (Figure 3) represents the case when the contract supports preventive maintenance, besides corrective maintenance. More precisely:

- i) a periodic inspection is offered in the contract to assess the equipment health state through potential signals of degradation; the inspection is part of PHM operations, and would lead to schedule a preventive repair based on the equipment health assessment and RUL prediction.

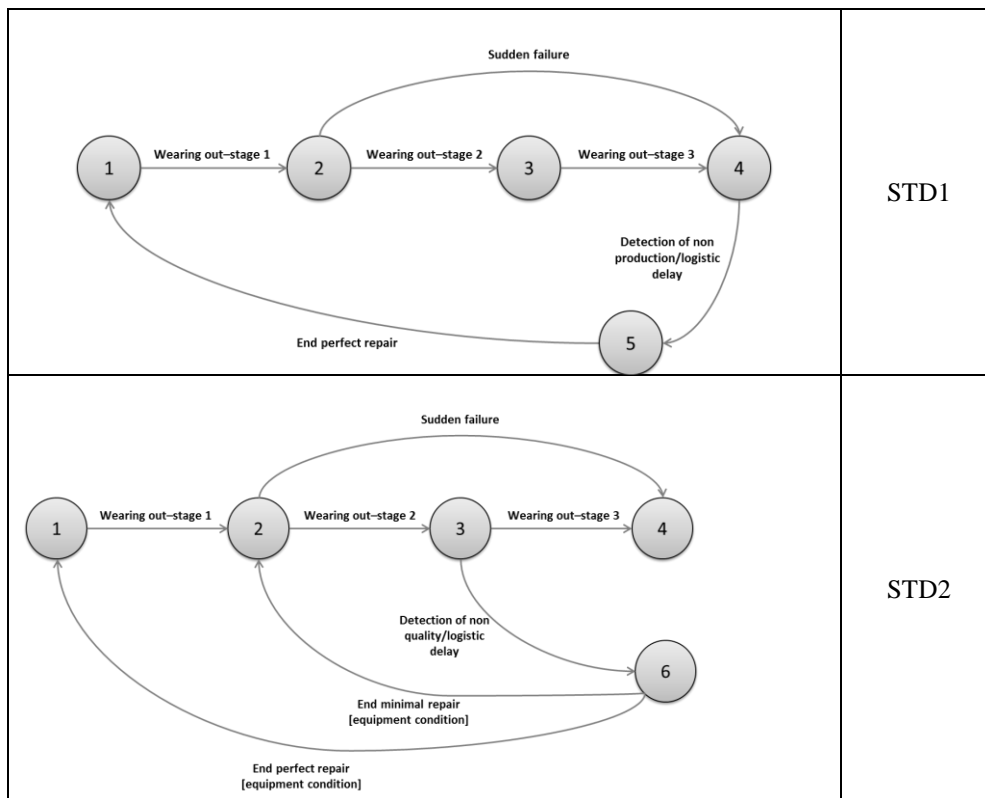


Figure 2 State transition diagrams of degradation and repair processes - corrective maintenance

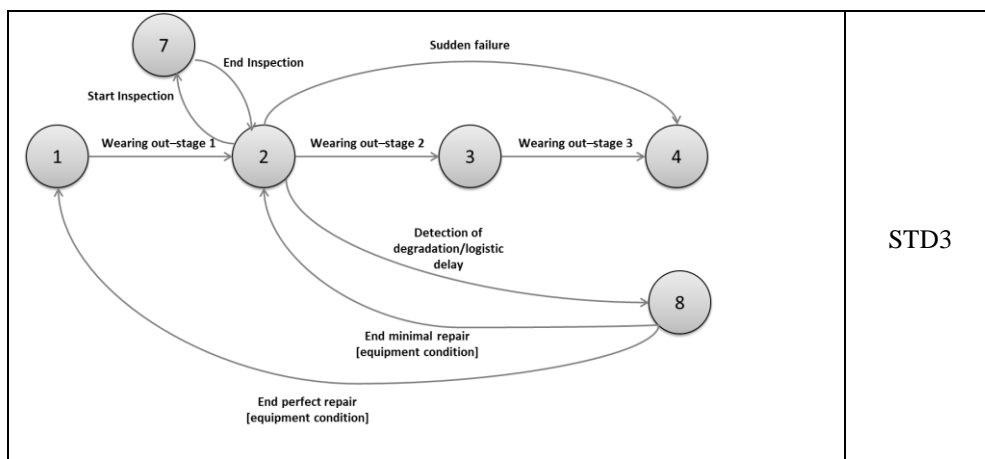


Figure 3 State transition diagrams of degradation and repair processes - preventive maintenance

Table 2 provides a further description of the states included in the STDs.

#	State	Description
1	Working as good as new	The equipment works as good as new after its first installation. The equipment also returns working as good as new every time a perfect repair is ended.
2	Working with potential signals of degradation	The equipment may provide potential signals of degradation after some time passes as effect of wearing out-stage 1. It may also provide potential signals of degradation after some time passes once a minimal repair is ended.
3	Product quality defects	The equipment may produce more defects with respect to the standard quality level accepted by the customer, after some time passes as effect of wearing out-stage 2.
4	Fault	The equipment stops subsequent to wearing out-stage 3 or a sudden failure.
5	Fault (unscheduled downtime)	The equipment is stopped for corrective repair, after the customer detects the fault leading to the equipment stoppage. Downtime is not planned in the production schedule.
6	Product quality defects (unscheduled downtime)	The equipment is stopped for corrective repair, after the customer detects product quality defects. Downtime is not planned in the production schedule.
7	Periodic Inspection (scheduled downtime)	The equipment is stopped for periodic inspection, to assess its health state through potential signals of degradation. Downtime is agreed with the customer, and planned in the production schedule.
8	Preventive repair (scheduled downtime)	The equipment is stopped for preventive repair, as a result of the inspection. Downtime is agreed with the customer, and planned in the production schedule.

Table 2 States along the degradation and repair processes

It is worth remarking that the degradation process – including states 1, 2, 3 and 4 – expresses the equipment reliability, which is a given characteristic. The repair process instead depends on the choices of maintenance logistics support offered in the service contract – represented by other states –. Some characteristics are given also in this case. Indeed, the STDs assume that maintenance intervention is executed according to given working standards, in regard to the decision of minimal or perfect repair: (i) when the fault state with complete equipment stoppage is reached, the replacement of worn-out or broken parts is necessary, leading to a perfect repair; (ii) when the intervention is issued subsequent to the product quality defects or the inspection results, it is decided whether making a minimal or a perfect repair based on the equipment condition. The minimal repair consists of a reconfiguration action – in the remainder cited to as conditioning intervention –, carried on to allow the equipment to continue its mission but at a reduced production speed.

3.3 Component object and data modelling

The State Based Model (SBM) – all the STDs – is the input driving the identification of the component objects required for maintenance logistics support: the resources and services (enabling system) provided through field service delivery to support the product/equipment (primary system). Table 3 enlists the resources and services identified as derivation of the SBM. Different resources would be needed depending on the type of field service delivery: for example, if the service contract is

represented by STD1, the relevant event within the contract boundaries is the *end perfect repair*; this requires service provider technician plus auxiliary resources, i.e. spare parts.

Event in the state transition	Service	Resource					
		1	2	3	4	5	6
Detection of non-production	---	X					
Detection of non-quality	---	X	X				
Start/End inspection	Inspection (assessing equipment health and predicting RUL)			X	X		
Detection of degradation	Scheduling of repair (based on inspection results)			X	X		
End minimal repair	Repair (conditioning)			X		X	
End perfect repair	Repair (part replacement)			X			X

Table 3 Services-resources *per* state transition (notation: 1 = Human resource (customer technician); 2 = Quality control chart (on the equipment); 3 = Human resource (service provider technician); 4 = E-maintenance tool; 5 = Equipment controller; 6 = Spare parts)

Component object modelling is applied on the identified objects, leading to a Conceptual Data Model (CDM) – UML based as formalism – for modelling the classes of component objects with their own relationships and attributes. Maintainability and supportability are described therein, thus representing the repair process through a set of attributes allocated to the resource and service objects (e.g. time to repair, time for logistic delay, maximum number of conditioning interventions before a perfect repair is required, ...). Instead, reliability is a property of the product/equipment target of support, modelled through the rates of state transitions along the degradation process of the equipment itself.

The data collection, to implement the SD model, is straightforward: the required templates can be derived by the CDM, and then implemented in appropriate tools (e.g. MSTM Excel).

3.4 System dynamics modeling

SD is the method used to simulate the degradation and repair processes with different alternatives of maintenance logistics support. In this regard, SD is flexible to express the events occurring within the primary and the enabling system, as required by the SBM. More than that, such flexibility is used to build a library of building blocks to be assembled – as “atoms” – to simulate the logics expressed in the different STDs.

The building blocks, derived breaking down in different “atoms” the STDs of Figures 2 and 3, are the followings:

- i) a time based transition (e.g. simulating the wearing out-stage 1);
- ii) a time based transition with mutually exclusive branches (i.e. simulating the wearing out-stage 2 or the sudden failure);
- iii) a time based transition with mutually exclusive branches dependent on a condition (i.e. simulating, depending on the equipment condition, the end minimal repair or the end perfect repair);
- iv) a time based transition with mutually exclusive branches and a set of rules to manage the branches (i.e. simulating either the start inspection, wearing out-stage 2, sudden failure or detection of degradation, based on a set of rules using timing parameters – RUL, time to the next periodic inspection, time to degradation or sudden failure – and quality parameters – regarding the accuracy of inspection results).

Assembling the building blocks allows to obtain the SD models capable to simulate the behaviours expressed in the SBM, considering the resources and services required at given transitions according to the CDM. Vensim Ple is the SD software tool used to develop the models.

3.5 Economic and environmental impact assessment

SD models provide simulated outputs to predict and analyse the economic and environmental performances along the equipment use life. A further extension of the CDM is required to this end, with the purpose to complete the data needed for measuring the performance indicators of interest. The economic assessment follows a double path, by measuring both the Life Cycle Cost (LCC) and the Overall Equipment Efficiency (OEE) of the product/equipment. The environmental assessment instead focuses on the energy use and subsequent carbon footprint, measured in terms of CO₂ equivalents.

Rebitzer et al. (2003) defines LCC as “*all costs associated with the system as applied to the defined life cycle*” and indicates that it is usually measured through the Net Present Cost indicator, which can be interpreted as Total Cost of Ownership (TCO) in case the focus is on the customer/user of the good in question.. In this regard, TCO includes the economic performance of maintenance service contracts, considering a service life cycle perspective. Besides visible costs of the service contract (contractual fees, spare part costs, etc.), hidden costs are taken into account, consisting in monetization of lower performance e.g. due to unavailability caused by unscheduled equipment downtime and to product quality defects.

OEE is a common indicator, obtained by breaking down the efficiency in three factors: Performance (P), Quality (Q) and Availability (A), thus measuring respectively efficiency in terms of production speed, production quality, and uptime for production. OEE is then equal to the multiplication of the factors: $OEE = P * Q * A$ (Oechsner et al., 2002). In a broad interpretation of the economic performance, OEE can be used as measure closely related to hidden costs: it relates to the quality of equipment use in terms of value added activities, helping to analyse possible paths for reducing non-value added ones, with subsequent improvement of the economic outcomes (Isaksson, 2005; Isaksson 2006; Reed et al., 2000; Svensson, 2006).

Considering a life cycle perspective similarly to LCC, a Life Cycle Energy consumption is also measured as the required kWh during the equipment use life. This evaluates separately the needed power as used in different equipment states (e.g. a machining state needs different power respect to idle state), and the respective time spent during the simulated equipment use life, which eventually enables to calculate how the energy is used.

The environmental impact assessment also considers the global warming potential generated by the production of electric energy used to run the equipment. In this regard, the most impacting gases are carbon dioxide (CO₂), dinitrogen monoxide (N₂O), methane (CH₄), whose CO₂-equivalence factors are respectively: 1, 310, 21 (Narita et al., 2006). The total CO₂ equivalents are computable as a sum of the contributions of most impacting substances, neglecting the impacts of less relevant chemicals. Each of these contributions can be obtained by multiplying the energy use times a factor that depends on the geographic area, on the mix of energy sources used to produce electricity and on the CO₂ unit emission for each type of energy source. Finally, this enables to know the emitted kg of CO₂ equivalents, correspondent to the energy use for the equipment use life. It is worth observing that, although the energy consumption and CO₂ emissions are not strictly proportional in general, in the application proposed for the methodology they would be correlated because the energy source mix is not differential under any scenario taken into account for the simulation.

Concluding, it is worth pointing out the following remarks:

- i) to make the economic and environmental impact assessment, some technical data should be integrated within the CDM, with the purpose to characterize the states of the product/equipment for their environmental impacts (e.g. power used at different equipment states) and effects on the overall efficiency (with concern to the production speed reductions and product quality defect rates);
- ii) the SD model also makes a correspondent computation of the different performances of interest; this would lead to consider indicators such as total required kWh and total cost of maintenance services during the equipment use life, OEE, CO₂ equivalents, and others (e.g. energy efficiency, ratio of hidden versus visible cost in the LCC, etc.).

4 The case study

4.1 Case introduction

FIDIA is a milling machine manufacturer. Quality of finished products and milling process, and productivity through high cutting speeds, are the most relevant machine features for FIDIA to compete. Energy savings has been increasingly recognized in recent years due to the requirements from customers, the increasing pressure of regulations, and the opportunities from technologies. This is aligned with the trend observed in the machine tool industry.

FIDIA is recently looking at after-sales services, especially at maintenance services, as an opportunity space for enhancing profitability and resource efficiency (energy, lubricants, spare parts...). This study is interesting to know how the use of advanced technologies may influence machine features, with special concern to quality and productivity as most relevant factors and energy as secondary factor, with the final aim to generate profits from maintenance services.

The case study focuses on a subsystem of the machine, i.e. the multiple mechanical axes moved by electric drives used to translate and rotate the milling head in the workspace. FIDIA is implementing a diagnostic tool running on the CNC of its machines, to aid the technicians in a predictive diagnosis, i.e. e-maintenance tool. In this scenario (Figure 4), the service department decides the configuration of a service contract by planning the allocation of field service technicians, spare parts, and the diagnostic tool on board: this e-maintenance tool, supporting PHM through on-site inspection or remote monitoring, is the solution envisaged when the service offering can exploit the technological developments currently on going.

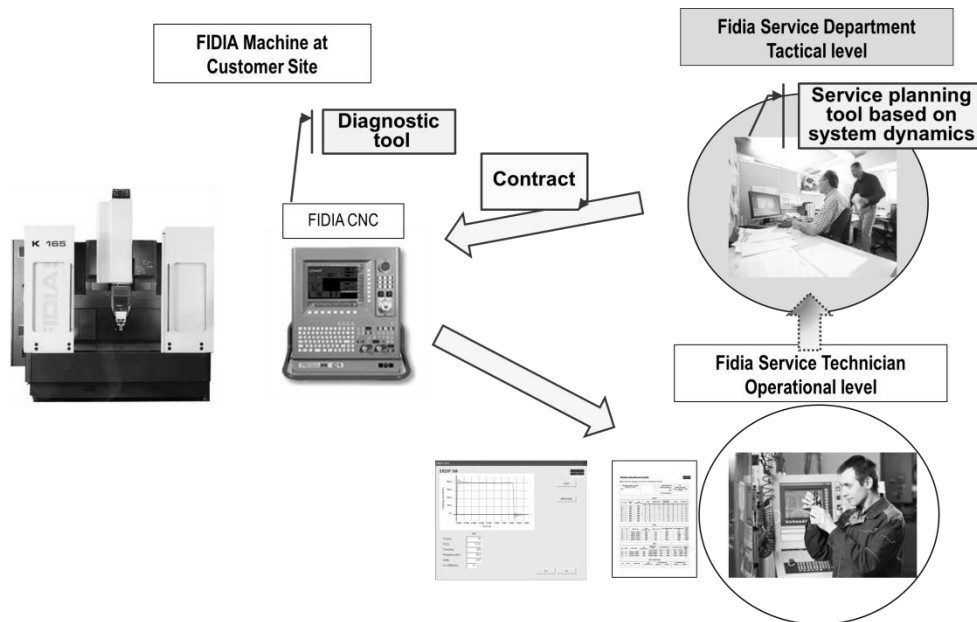


Figure 4 Field service delivery enhanced by an e-maintenance tool

Anyhow, it is also a planning problem: the expected frequency of maintenance interventions, resulting from either a corrective or mix between corrective and preventive maintenance, is the main driver. The frequencies should be defined based on the customer requirements: it is not a default that offering a preventive maintenance in the service contract is always the best choice; the corrective maintenance sometimes might be sufficient.

4.2 Economic and environmental impact assessment

Economic and environmental impact assessment is herein demonstrated by showing how it could support decisions of the service department.

Once the SD models are built for the different alternatives to offer in the contract, data collection is needed. Data sources are different due to the variety of attributes defined by the CDM. Stochastic data models have been assumed for reliability, maintainability and supportability. In this regard, the experts of the service department have been asked estimates on different indicators (e.g. time to degrade at different wearing out stages, time to repair, time to wait for the logistic delay), basing on historical recordings at FIDIA service centres and their expertise. Other technical data have been kept as deterministic values, being sourced from technical catalogues (e.g. the standard power usage and production speed), working standards (e.g., the maximum number of conditioning interventions acceptable before part replacement), and external sources (i.e. CO₂ equivalent factors).

The results shown in the remainder come out from experiments along the machine use life (15 years), done using the SD models. Two assumptions stand for the simulated experiments: (i) a customer type is considered, with given processing requirements; (ii) PHM works with a perfect visibility on future

events, without any uncertainty on the RUL. Results are then analysed by studying the trend of average values and box plots of the performances, built separating data in 25th – 75th percentiles.

Figure 5 shows the trade-off of OEE factors resulting from adopting alternative solutions in the service contract. Even if box plots are partially overlapping, it is worth observing the best result obtained for Availability A when using a PHM program; conversely, Performance P is not a good outcome for PHM, this can be motivated by a better understanding of the dynamics of conditioning interventions. Then, Figure 6 focuses on how the number of conditioning interventions increases with longer time between inspections (Graph a), which results in a subsequent reduction of Performance P (Graph b). In particular, the figure (Graph a) quantifies an expectation: a longer time between inspections leads a technician to anticipate the conditioning intervention, so avoiding the risk that product quality defects or fault would happen before the next inspection is scheduled. This behaviour results in higher number of conditioning interventions, subsequently, in higher production speed reductions, as result of preventive repair, which finally motivates the result shown for the Performance (in Graph b).

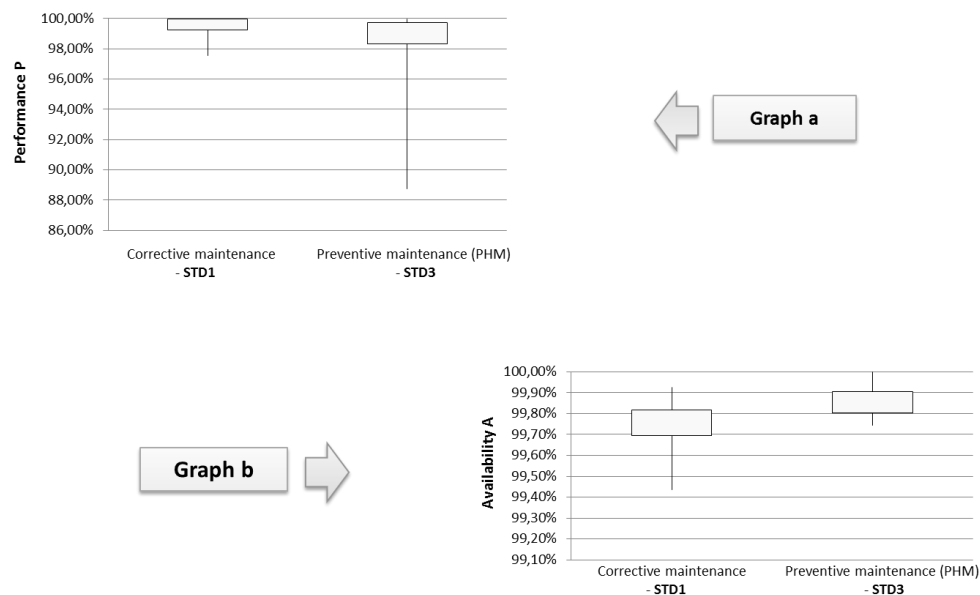


Figure 5 Performance and Availability with different maintenance services

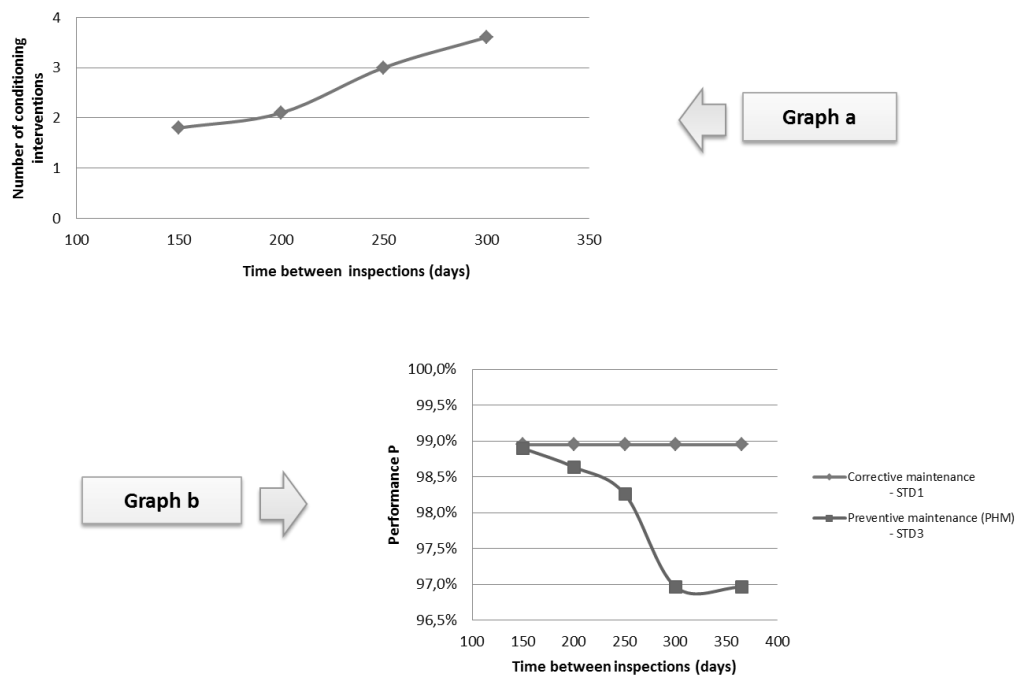


Figure 6 Effects of time between inspections in a preventive maintenance service

The low Performance has an effect on the Life Cycle Energy consumption. Even if it shows higher variance (and box-plots are partially overlapping), this measure is lower with corrective maintenance (Figure 7). As a result of conditioning, the mechanical axes move slowly (Graph a in Figure 5), but power consumption can be assumed still the same; then, the machine works less products per hour, which is the reason for a growth of energy inefficiency and Life Cycle Energy consumption and, given the energy sources, CO₂ equivalents.

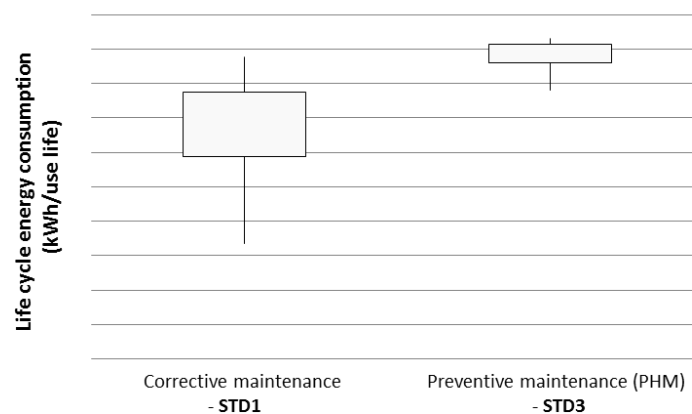


Figure 7 Effects of different maintenance services on energy consumption

Figure 6 helps a further deduction: a minor time between inspections is equivalent to continuous monitoring and, in this case, the expectation from the graphs is for a minimum number of conditioning interventions (Graph a) and a Performance P at its highest level (Graph b). Hence, a PHM program also tends to enable the achievement of high P (hence, a reduction of Life Cycle Energy consumption) if a continuous monitoring is adopted. This is clearly related to a solution using PHM in a remote way, without the inspection on-site.

Economical concern is needed to justify whether a PHM program with a given inspection period is convenient or not. A sensitivity analysis of the total cost of the service contract is shown in Figure 8. Assuming a variation of the unitary hidden cost due to machine unavailability (i.e. to unscheduled downtimes), an equilibrium point is approached at the highest values: the higher is unitary hidden cost with respect to equilibrium point, the higher is the convenience of running the PHM program.

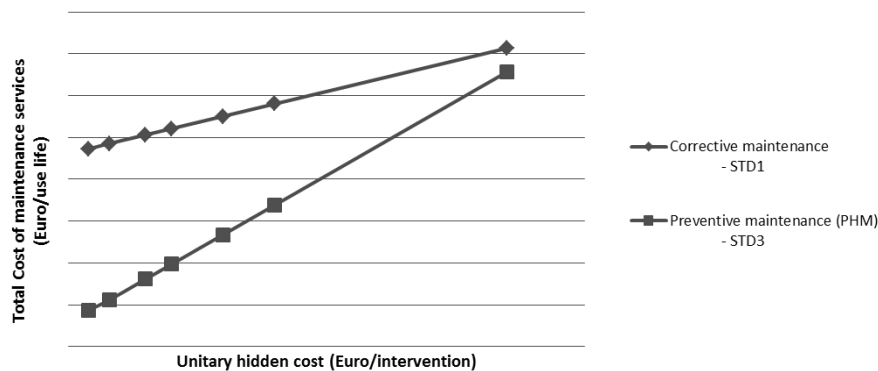


Figure 8 Sensitivity analysis on total cost of different maintenance services

If the hidden cost keeps into account also product quality defects, considering the logic of a PHM program (STD3, Figure 3) economic convenience may be even higher. In this regard, it is worth remarking that the unitary hidden cost for non-qualities is relevant for FIDIA's customers in some market segments: this calls for a customer segmentation, expressing the customer requirements by the hidden cost related to unavailability and/or product quality defects.

4.3 Concluding remarks

The demonstration shown in the case study provides a concrete evidence to support the theories present in literature: a PHM program would bring advantages for economic and environmental sphere. A recommendation is worth full, when conditioning interventions are used as standard to reconfigure machine parameters, thus reducing production speeds: it seems advisable to apply PHM in a continuous monitoring mode; this would enable approaching a frequency of conditioning interventions in line with inherent degradation rates, without the burden of corrective maintenance.

5 Conclusions

The paper proposes a study of economic and environmental performances concerning different configurations of maintenance services offered by a machine tool builder for a machine at a customer site. The results obtained through system dynamics have shown that a field service enhanced by the technological support of an e-maintenance tool releasing PHM based on remote monitoring can be a promising option for OEE and costs, particularly relevant when the total cost of maintenance services includes the hidden costs of machine unavailability and product quality defects. The energy use – so, the carbon footprint – is also reduced by supporting the PHM program through remote monitoring. Overall, the paper contributes to the exploration of the role that technological innovations can bring to the provision of maintenance services in industry, considering product and service life cycle perspectives, with the ultimate purpose to analyse their effects on the economic and environmental sphere. The contribution is reinforcing theories discussed in the domain of sustainable manufacturing, particularly proving by experimental approach the expectations on benefits of technology-enhanced maintenance to sustainability.

The limitations are subsequent to the experimental scope, focused on one customer at a given site, while the complete assessment of field service should consider a network level. Next researches will consider an extension of impact assessment at network level, with more machines and customers: it will be worth studying the organisational and operational decisions at network level, and the resulting economic and environmental impacts. Regarding the use of system dynamics, it will be relevant to extend the building concept of simulation models suggested in the paper, considering more machines in the network.

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